GCA TECHNICAL REPORT NO. 63-28-N

34 p.

N64 12097
CODE-1
NASA CR-55113

OTS PRICE

XEROX $ 3.60 ph

MICROFILM $ 1.22 mf

CR-55113

GEOPHYSICS CORPORATION OF AMERICA BEDFORD, MASSACHUSETTS

PLANETARY AERONOMY XVI: CORPUSCULAR RADIATION IN THE UPPER ATMOSPHERE

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CONTRACT NO. NASw-701

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HEADQUARTERS
WASHINGTON, D. C.
OCTOBER 1963

GCA Technical Report No. 63-28-N

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CORPUSCULAR RADIATION IN THE UPPER ATMOSPHERE

A. Dalgarno Oct. 1963 34p refs Presented at the IUGG meeting, Berkeley, Calif., 19-24 Aug. 1963 Submitted for Publication

☒ OTS

☐ Conf

October 1963

3599487

GEOPHYSICS CORP~~ORATION~~ OF AMERICA

Bedford, Mass~~achusetts~~

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(NASA Contract No. NASw-701)

(NASA CR-55113; GCA-TR-63-28-N) OTS: \$3.60 ph, \$1.25 mf

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
HEADQUARTERS
WASHINGTON, D. C.

Invited paper presented at IUGG Meeting held in Berkeley, California, on August 19-24, 1963. This paper has been accepted for publication in Annales de Geophysique.

ABSTRACT

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The efficiencies of fast electrons and protons in producing luminosity and heating by collisions with the atmosphere are discussed and upper limits to the fluxes of corpuscular radiation are obtained. A possible explanation of high-altitude red auroras is advanced. The effects of the photoelectrons produced in the ionization of the atmosphere by extreme solar ultraviolet radiation are examined and it is noted that the electron temperature at high altitudes may be anomously large at dawn, the phenomenon being accompanied by a red glow.

It is suggested that the source of 1304Å dayglow radiation postulated by Donahue and Fastie is excitation by impact of fast photoelectrons and that fast photoelectrons may lead to a large dayglow intensity of the first positive system of nitrogen through resonance scattering by metastable molecules. AUTHOR

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1. INTRODUCTION

It is clear from the occurrence of visible auroras and of polar cap and auroral absorption that corpuscular radiation is an important energy source in the upper atmosphere at high latitudes and various indirect arguments have suggested that it is also an important energy source at middle and low latitudes. Some of the consequences of a flux of corpuscular radiation are examined in this review.

2. LUMINOUS EFFICIENCY OF FAST ELECTRONS

2.1 Emission from N_2^+

There is an important argument (Omholt [1]) which relates the energy flux of a beam of fast electrons absorbed by the atmosphere to the resulting intensity of the first negative system of molecular nitrogen. Stewart [2] has measured the cross sections for production of the 0-0, 0-1 and 0-2 bands

$$e + N_2(X'\Sigma_g^+) \rightarrow e + N_2^+(B^2\Sigma_u^+) + e \quad (1)$$

by the impact of electrons with energies up to 200 eV and finds that the variation with energy is very similar to that of the total ionization cross section

$$e + N_2(X'\Sigma_g^+) \rightarrow e + N_2^+ + e \quad (2)$$

(Tate and Smith [3], Fite and Brackmann [4]). The cross sections for the production of the 0-0, 0-1 and 0-2 bands are respectively about 2%, 0.7% and 0.2% of the total ionization cross section. Since the mean energy expended in the production of an ion pair by a beam of fast electrons absorbed in nitrogen is 35 eV (cf. Valentine and Curran [5]), it follows that the efficiency with which energy is converted into radiation is about 2×10^{-3} for the 0-0 band at 3914Å, about 7×10^{-4} for the 0-1 band at 4278Å and about 2×10^{-4} for the 0-2 band at 4709Å.

When the initial energies of the fast electrons fall below perhaps 100 eV, these efficiencies must decrease sharply (cf. Dalgarno and Griffing [6]).

Hartman and Hoerlin [7] have measured the efficiency of energy conversion into 3914Å radiation of a beam of electrons absorbed in air at sea level. They obtained an efficiency of 3.3×10^{-3}, independent of the electron energy which was varied from 200 eV to 1000 eV. Correcting for the oxygen content, the efficiency for absorption in nitrogen is about 4×10^{-3}, a value which is twice that derived from cross section data. Some of the discrepancy may be attributed to the deactivation of more highly vibrating molecules through processes such as

$$\begin{aligned} &N_2^+(B^2\Sigma_u^+, v) + N_2(X'\Sigma_g^+, 0) \\ &\rightarrow N_2^+(B^2\Sigma_u^+, 0) + N_2(X'\Sigma_g^+, v) \quad . \end{aligned} \tag{3}$$

The value of the energy conversion coefficient appropriate to the upper atmosphere depends upon the fractional content of N_2 at the altitude at which the electrons are absorbed. To avoid complicating the argument, I shall adopt 1×10^{-3} for the efficiency with which energy is converted into 3914Å radiation so that a flux of ζ erg cm^{-2} sec^{-1} gives rise to 200 ζ rayleighs. I am indebted to Dr. Roach for the remark that 60 rayleighs of 3914Å emission would not occur undetected from which it follows that the possible flux of fast electrons at middle and low latitudes cannot exceed 0.3 erg cm^{-2} sec^{-1}. It might be possible to place a smaller upper bound if a systematic search for N_2^+ emissions were made at middle and low latitudes. Indeed, Galperin [8] has stated that for the long night exposures in Zvenigorod at a geomagnetic latitude of 51.1°N, the absence of observable emission shows that the intensity of the 4278Å band does not exceed 1.5 rayleighs. Adopting an energy conversion coefficient of 3×10^{-4}, it follows that the flux of energetic electrons cannot exceed 2×10^{-2} erg cm^{-2} sec^{-1}, a result in close agreement with the limits derived by Galperin [8]. The derived upper limit is comparable to the value of the average flux of dumped electrons with energies greater than 1 keV at midlatitudes over North America, estimated by O'Brien [9] from Injun 1 data on outer zone electrons, and to the average fluxes recorded by Antonova and Ivanov-Kholodny [10] and by Kazachevskaya and Ivanov-Kholodny [11] at altitudes between 70 km and 100 km. The intensity of the electron fluxes fluctuates markedly in time (Ivanov-Kholodny[12])

Ivanov-Kholodny and Antonova [13], Antonova and Ivanov-Kholodny [14], Danilov [15] and Ivanov-Kholodny [16] have advanced the hypothesis that the persistence of the ionosphere through the night is due to a flux of energetic electrons. According to their analysis, the required flux is greater than 1 erg cm^{-2} sec^{-1} which considerably exceeds the derived limits. Thus, either the nocturnal ionization hypothesis or the theoretical analysis must be rejected.

A corpuscular flux has also been invoked by Mariani [17] in order to explain the correlation of maximum electron density in the F region at noon with solar activity. For high-solar activity, Mariani postulates a flux of about 0.1 erg cm^{-2} sec^{-1} of electrons with energies of the order of 1 keV, peaking at geomagnetic latitudes between 55° and 65°. It is of interest to note that if the maxima of the outer radiation belt at 1000 km are projected along local magnetic lines of force, the maximum at 100 km occurs at a magnetic latitude between 56°N and 57°N (Winkler [18]). The distribution with latitude is broadly similar to that found by O'Brien [9] for the time average of electrons with energies above 40 keV precipitated into the atmosphere at an altitude of 1000 km, which also peaks between about 60°N and 65°N. However, the shapes of the distributions at higher latitudes are very different, as are the electron energies involved.

The flux derived by Mariani gives rise to at least 20 rayleighs of 3914Å emission and it is of interest to compare this intensity with those observed at night in the absence of auroras. It may be relevant to note that O'Brien [19] found that the flux of geomagnetically trapped electrons with energies greater than 40 keV at an altitude of 1000 km shows little diurnal variation for magnetic latitudes less than about 63°N (strictly for $L \leq 5$, where L is the coördinate introduced by McIlwain [20]).

Observing at a magnetic latitude of 60.5°N, Lytle and Hunten [21] found a permanent intensity of about 30 rayleighs during 1960 and probably less than 20 rayleighs during 1961. Russian workers (cf. Galperin [8], Mulyarchik and Shcheglow [22]) found greater intensities at Loparskaya at the slightly higher geomagnetic latitude of 63.7°N, the associated fluxes being about 1 erg cm^{-2} sec^{-1} at maximum solar activity and 0.3 erg cm^{-2} sec^{-1} at minimum solar activity. These observations are consistent with the view that corpuscular radiation is an important source of ionization in the F region at geomagnetic latitudes near 60°.

Van Allen and his collaborators [23] have observed a permanent flux of electrons at low altitudes, the maximum intensity occurring between 65°N and 70°N. Most of the electrons have energies between 10 keV and 100 keV and the maximum energy flux lies between 0.1 and 1 erg cm^{-2} sec^{-1}. The energy spectrum is consistent with Mariani's analysis which suggests that corpuscular radiation is not an important source of ionization in the F layer at latitudes much above 60°N so that the incident particle flux should not include a large component of electrons with energies of less than 1 keV.

The conversion efficiency for producing 3914Å radiation has been used by Sharp et al. [24] in an analysis of satellite measurements of particle fluxes during auroras. From ground-based observations of 3914Å emission (Belon et al. [25]), they conclude that the energy flux was at least 100 erg cm^{-2} sec^{-1} whereas the measured flux of electrons with energies greater than 2 keV indicated a total intensity of only 10 erg cm^{-2} sec^{-1}. Thus, either the energy spectrum rises very steeply at low energies or an acceleration mechanism is operating [24].

2.2 Other Emissions

There are few quantitative data on the efficiencies for converting electron kinetic energy into radiations other than those of the first negative system. Hartman and Hoerlin [7] have obtained an efficiency of 1.5×10^{-2} for converting the energy of 200 eV - 1000 eV electrons absorbed in air at sea level into radiation between 3000Å and 10,000Å. About one-third of the energy is emitted in the first positive band system of $N_2(C^3\pi_g \rightarrow A^3\Sigma_u^+)$ (Hartman and Hoerlin, private communication 1963). The measured efficiency is unexpectedly high, for very little intensity is to be expected from molecular band systems of O_2 and O_2^+ or from atomic lines and a deactivation mechanism such as (3) is probably rapid enough to present any observable emission of the infrared Meinel bands of $N_2^+(A^2\pi_g - X^2\Sigma_g^+)$, the 0-0 band of which is located at 11,036Å. Presumably, a considerable fraction of the luminosity must be emitted in the second positive system of $N_2(C^3\pi_u - B^3\pi_g)$ in the region between 3000Å and 4000Å and in particular at 3371Å, 3577Å and 3805Å corresponding respectively to the 0-0, 0-1 and 0-2 bands.

Because of the lower frequency of quenching collisions, larger values of the conversion efficiency should be appropriate in the upper atmosphere. The value of 2×10^{-3} derived by McIlwain [26] from an analysis of simultaneous observations of particle fluxes and luminosity intensity in a quiescent auroral glow at an altitude of about 120 km is therefore unexpectedly low. Thus, the first negative system of N_2^+ should alone contribute more than 2×10^{-3} and a comparable amount is to be expected from the green line of atomic oxygen at 5577Å, for it has been observed that the ratio of the intensity of 5577Å line to that of the 3914Å band is nearly constant at a value between 1 and 2 over a wide range of auroral intensities, for various auroral forms and probably over a wide height interval (cf. Chamberlain [27]). Chamberlain [27] has suggested that the smallness of the ratio of 5577Å to 3914Å may be due to the removal of electrons, that would otherwise excite the green line, by excitation of the nitrogen bands in exchange collisions. However, there is another mechanism which may also contribute to the low ratio.

Fast electrons of energy E eV lose energy in elastic collisions with the ambient thermal electrons at a rate

$$\frac{dE}{dx} = -\frac{2 \times 10^{-12}}{E} n_e \text{ eV cm}^{-1} \tag{4}$$

where n_e is the number density of the thermal electrons whereas they lose energy in exciting O('S) at a rate of about

$$\frac{dE}{dx} = -2 \times 10^{-17} n(0) \text{ eV cm}^{-1} \tag{5}$$

where n(0) is the number density of atomic oxygen (Dalgarno, McElroy and Moffett [28]). Thus, for a bright aurora of IBC III for which $n_e \sim 5 \times 10^6$ cm^{-3} at an altitude of 120 km where $n(0) \sim 5 \times 10^{10}$ cm^{-3}, fast electrons lose energy more rapidly in heating the ambient electron gas than in exciting the green line whenever their energy falls below 10 eV.

An appreciable contribution to the energy conversion coefficient should also appear in the second positive bands of N_2 but uncertainty as to the spectral sensitivity curve of the photometer employed prohibits any estimate of the importance of the first positive bands of N_2, the Meinel bands of N_2^+ and the atmospheric bands of O_2, all of which are probably produced with high intensities.

McIlwain [27] remarked that the probable error in his estimate of 2×10^{-3} is about a factor of two and that it is unlikely to be in error by more than a factor of four. A value of 6×10^{-3} seems a reasonable compromise with an approximately equal distribution in the first negative system of N_2^+, the first positive system of N_2 and the green line of atomic oxygen.

Anderson and DeWitt [29] observed 60 kilorayleighs of green line emission from a widespread auroral glow over Alaska, implying an energy flux of about 250 erg cm^{-2} sec^{-1}. Taken together with their balloon measurements of X-rays, this suggests that only 1 percent of the luminosity is contributed by electrons with energies of more than 25 keV.

3. LUMINOUS EFFICIENCY OF FAST PROTONS

3.1 Emission from N_2^+

The cross sections for allowed transitions are approximately equal for fast electrons and protons of the same velocity and explicit confirmation of this theoretical prediction has obtained for the ionization of N_2 (Hooper, Harmer, Martin and McDaniel [30]). Since a considerable fraction of the excitation and ionization produced by the absorption of fast protons is due to the secondary electrons, the coefficient for the conversion of the proton kinetic energy into radiation in the N_2^+ first negative system should be much the same as for fast electrons. It may actually be somewhat greater because of the additional contribution from charge transfer excitation

$$H^+ + N_2(X'\Sigma_g^+) = H + N_2^+(B^2\Sigma_u^+) \quad . \tag{6}$$

Thus, the relationship between the intensity of 3914Å radiation and the incident energy flux given in Section 2.1 is largely independent of the nature of the fast particles involved.

3.2 Emission from H

The most recent analysis of the absorption of a beam of fast protons in air is that of Chamberlain [27] who shows that about 60 quanta of H_α and about 16 quanta of H_β are produced. These values are independent of the initial energy (provided it is large enough) because the probability of capture decreases very rapidly at high velocities. Accordingly, observations of Doppler-shifted hydrogen lines yield information only on the particle flux and additional data are required to determine the energy flux.

Measurements by McIlwain [20] of protons in a quiescent auroral glow using rocket-beam detectors yield a proton energy flux of

$$j(>E) = 2.5\times10^{6} \exp(-E/30)\ \mathrm{cm}^{-2}\mathrm{sec}^{-1}\mathrm{ster}^{-1} \qquad (7)$$

for proton energies between 80 and 250 keV, E being measured in keV. By assuming that (7) may be extrapolated to zero energy and that the angular distribution is isotropic, McIlwain obtains a particle flux of 1.6×10^{7} cm^{-2} sec^{-1} which on comparison with the ground-based observations of H_β (Montalbetti [31]) yields a value of $4H_\beta$ quanta for each incident proton. In view of the many uncertainties, the agreement with the theoretical value of 16 quanta is satisfactory.

The additional information required to determine the energy flux cannot be provided directly by the measurements of the intensity ratio of N_2^+ and H emissions because the former is also produced by electron impact, but it can be provided by observations of the emission altitudes. Thus, it has been shown (Omholt [1,32], Chamberlain [27]) that in an aurora produced by monoenergetic protons at an altitude of about 120 km, the ratio of the intensities of 3914Å and H_β emission is about unity and it decreases as the altitude of the aurora increases. The observed ratio is nearly always, and often much greater than ten, and it is therefore highly improbable that any ordinary aurora is produced mainly by proton bombardment ([1], [32], [27]). It may also be shown [27] that for bright auroras above an altitude of 100 km with a flux of 10 kilo-rayleighs of H_α (which is near the maximum observed), the energy flux of fast protons is about 10 percent of the total energy deposited as evidenced by the emission rate of 3914Å. The discrepancy does not necessarily imply a significant difference between the fluxes of electrons and protons in an aurora since a large proportion of the incident protons could have low velocities and produce no radiation. If present, the undetected slow protons may be an important source of atmospheric heating during an aurora.

According to Galperin [8], the intensity of Doppler-shifted H_α emission does not exceed 3 rayleighs at low and middle latitudes. He concludes that the proton energy flux must be less than 6×10^{-4} erg cm^{-2} sec^{-1} and that the associated heat flux must be smaller still. This argument does not take account of the low efficiency for producing radiation of protons with energies less than 1 keV, an efficiency which is anomously low because of the accidental resonance

$$H^+ + O \rightarrow H + O^+ \quad . \qquad (8)$$

4. HEATING EFFICIENCY OF ELECTRONS

4.1 Recombination Heating

A fast electron loses energy in exciting and ionizing the atmospheric constituents. The electrons ultimately become thermalized and are removed mainly by processes of dissociative recombination, which yield atoms with excess kinetic energy. There have been several discussions of the fraction of total electron kinetic energy which is converted into heat energy but neither the arguments nor the conclusions differ in any substantial way from those put forward by Bates [33], who concludes that the fraction is probably about 0.2. However, a value as high as 0.5 cannot be excluded.

It follows that a flux of S rayleighs of 3914Å emission is associated with a heat flux of about 10^{-3} S erg cm^{-2} sec^{-1} from recombination heating. Adopting the estimate of Galperin [8] for the maximum intensity of 3914Å emission, the heat flux at middle and lower latitudes due to fast corpuscular radiation in the nocturnal atmosphere is less than 8×10^{-3} erg cm^{-2} sec^{-1}. This upper limit is much greater than the heat flux postulated by Paetzold and Zschörner [34], Paetzold [35], Harris and Priester [36] and Jacchia [37]. The postulated heat flux is usually identified as arising from the dissipation of hydromagnetic waves (Dessler [38]) but it is useful nevertheless to note that it cannot be attributed to fast particles colliding in the upper atmosphere.

At the higher latitude of Loparskaya at 63.7 N, the heat flux in the absence of auroras varies from about 0.2 erg cm^{-2} sec^{-1} at maximum solar activity to about 0.07 erg cm^{-2} sec^{-1} at minimum solar activity. Except at high altitudes where diffusion is important, the distribution with altitude of the recombination heat source will be similar to those of the production of ionization and the production of N_2^+ radiation. Using the measurements of Grün [39], which are in harmony with the theoretical predictions of Spencer [40], Rees [41] has computed the altitude profiles of the ionization and N_2^+ emission produced by fast electrons. The influence of the magnetic field is not taken into account and the calculations are strictly appropriate only to high latitudes, as Rees notes.

The calculations by Rees show that for monoenergetic electrons with energies greater than about 5 keV, most of the heat energy is deposited in regions of limited altitude extent below 140 km and that as the energy decreases, the minimum altitude and the altitude extent of significant heat deposition increase. Thus, 1 keV electrons penetrate to an altitude of 150 km and the heat deposition per unit volume decreases by only a factor of four as the altitude increases from 180 km to 280 km.

The importance of the heat source implied by the observations of N_2^+ emission at high latitudes is accordingly strongly dependent upon the energy spectrum of the incident corpuscles. Satellite drag data do not show any large increase in the exospheric temperature at high latitudes (Jacchia [42]) which suggests that the energy spectrum of the incident corpuscles in quiet conditions does not contain a significant component of soft electrons. A corpuscular heat source may be responsible for the apparent increase with latitude of the rotational temperature of the OH airglow band system, but it may be an altitude effect (cf. Hunten [43], Wallace [44]).

There is evidence from direct measurements of corpuscular radiation (McIlwain [20]; Meredith, Davis, Heppner and Berg [45]; Anderson and DeWitt [29]; Sharp et al. [24]) that the energy spectrum during auroras often contain large components of soft electrons and significant local heating must occur. For 1 keV electrons, the initial rate of temperature rise is constant above 240 keV and equals 10^{-9}°K per minute for unit flux of electrons. Thus, in a bright aurora the initial rate of temperature rise will exceed 100°K per minute.

Measurements of the Doppler width of the oxygen red line during auroras by Mulyarchik [46] have shown a correlation between the intensity and width of the red line, suggesting that the heating increases with auroral intensity. For a strong bright red aurora, the width was equivalent to a temperature of 3500°K. Some care is needed in interpreting the observed temperature since, should the O('D) atoms be produced by dissociative recombination, they would initially possess excess kinetic energy. At altitudes above 350-400 km, the O('D) atoms will radiate before they are thermalized by elastic collisions.

An upper limit to the kinetic temperature of the high atmosphere can be obtained from observations of the red line. The intensity of the red line from thermal excitation at a kinetic temperature of 2000°K above 200 km is about 200 rayleighs and at a kinetic temperature of 3000°K it is about 20 kilorayleighs. The red line in the night airglow has typically an intensity of between 50 and 100 rayleighs (cf. Chamberlain [47]).

Occasionally, the red line appears with enormous intensity. Thus, in the great red aurora of February 11, 1958, the ratio of 6300Å to 5577Å was about 2.5×10^3 and the intensity of the 6300Å line attained a value of 10^5 kilorayleighs at one time (Manring and Pettit [48]). As Chamberlain [27] has argued, the green line had an intensity corresponding to IBC II so that the total particle flux and associated heating were presumably not unusually large. A possible explanation of such events emerges from an examination of heating by direct impact processes.

4.2 Impact Heating

Fast electrons which penetrate deeply into the atmosphere lose energy initially in exciting and ionizing the atmospheric constituents. As they are slowed down to energies of less than 7 eV, they lose energy predominantly in vibrational excitation of molecular nitrogen and less efficiently in exciting atomic oxygen into the 'D and 'S levels. The last electron volt of energy is usually lost by elastic collisions with the ambient electrons which provide a means of selectively heating the electron gas. The slowing down by excitation of the vibrational levels of nitrogen may also provide a path for selective heating of the electron gas depending upon which mechanism prevails for deactivating the vibrationally excited molecules [28]. However, because of the efficiency of cooling mechanisms at low altitudes, no large departure from equality of the electron temperature and the neutral gas temperature is to be expected (unless electric fields are present) in the altitude region near 110 km where most auroras are located.

The situation is very different for slower electrons which do not penetrate deeply into the atmosphere and which lose a large fraction of their energy in elastic collisions. Thus, 400 eV electrons penetrate to an altitude of 215 km [41] in producing excitation, ionization and secondary electrons. The distribution is approximately uniform over an altitude extent of perhaps 200 km. At these altitudes, the secondary electrons lose almost all their energy in elastic collisions with the ambient electrons leading to an energy conversion coefficient of about 0.1.

A convenient parameter for assessing the possible effect on the electron temperature T_e is the critical heat flux density Q_c eV cm^{-3} sec^{-1}, defined by

$$Q_c = \frac{2 \times 10^{-7} n_e^{2}}{\sqrt{T_i}} \qquad (9)$$

where T_i is the positive ion temperature [28]. If the actual heat flux density exceeds Q_c, T_e is not limited by energy transfer to the positive ions (Hanson and Johnson [49]) and it moves to a new equilibrium value determined by the efficiency of cooling by collisions with the neutral particles [22]. At high altitudes, the new equilibrium value of T_i will exceed $3T_i$. In order that such high values of T_i may occur between, say, 320 km and 420 km, it is sufficient to deposit there a heat energy of about 6×10^9 eV cm^{-2} sec^{-1} for an assumed mean electron density of 3×10^5 cm^{-3}. Such a heat source can be supplied by a flux of 400 eV electrons of about 0.2 erg cm^{-2} sec^{-1}.

Above 300 km, the most efficient cooling mechanism at the high equilibrium value of T_i, which is in the region of 5000°K, is electron impact excitation of the 'D level of atomic oxygen. Thus, a flux of 0.2 erg cm^{-2} sec^{-1} of 400 eV electrons may produce 3 kilorayleighs of red line emission.

Large fluxes are required to explain the great red auroras. To produce 10^4 kilorayleighs of red line emission, a flux of about 600 erg cm^{-2} sec^{-1} is required of which 30 erg cm^{-2} sec^{-1} appear as 6300Å photons. Because the efficiency of cooling increases rapidly with increasing electron temperature, the larger flux will not cause any great increase in T_e. The postulated mechanism for the production of the red line gives rise to essentially no green line emission. The observed green line intensity can be attributed to incident electrons with higher energies penetrating more deeply into the atmosphere, the required flux being about 20 erg cm^{-2} sec^{-1}.

The slow secondary electrons produced below 300 km will lose energy in exciting the vibrational levels of N_2 rather than in elastic collisions with the ambient electrons. This may be reflected in an unusual vibrational development of the first negative system of nitrogen which is apparently a feature of low latitude, high altitude red aurora ([27]).

An alternative explanation of the red auroras has been proposed by Megill and Carleton [50] who remark that they are almost certainly caused by local electric fields.

In normal aurora, the red line intensity is less than 15 kilo-rayleighs so that the incident flux of soft electrons should not exceed 1 erg cm^{-2} sec^{-1}.* Similarly in the undisturbed airglow, for which the intensity is less than 100 rayleighs, the flux of soft electrons should not exceed 0.2 erg cm^{-2} sec^{-1}.*

Limits to the flux of soft electrons may also be derived from the observed equality of the electron and ion temperatures at night. I shall return to this possibility in Section 6.2.

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*There is some question as to whether a configuration in which the electron temperature is essentially a discontinuous function of altitude is stable. The limits on the possible fluxes are correspondingly tentative.

5. HEATING EFFICIENCY OF PROTONS

5.1 Recombination Heating

It follows from arguments similar to those presented in Section 3.1 that the efficiency of recombination heating due to fast protons is comparable to that due to fast electrons so that the heat fluxes given in Section 4.1 are largely independent of the nature of the incident particles. If the permanent N_2^+ emission at high latitudes is due mainly to fast protons, the associated heat flux is unimportant since the protons necessarily penetrate deeply into the atmosphere. Of greater significance to the heating of the upper atmosphere is the possible flux of slow protons which do not produce radiation but instead lose energy through process (8) and by elastic collisions. As for electrons, the absence of a large increase in the exospheric temperature at high latitudes suggests that the component of soft protons is small. A quantitative examination of the possible heating would be of value.

5.2 Impact Heating

The energy loss of protons by elastic collisions with the charged particles of the ionosphere is inefficient compared to the energy loss in elastic collisions with the neutral particles.

6. EFFECTS OF FAST PHOTOELECTRONS

The photoelectrons produced by the absorption of extreme solar ultraviolet radiation in photoionizing processes constitute a source of corpuscular radiation in the daytime ionosphere.

6.1 Luminosity

The fast photoelectrons slow down through collisions with the neutral particles and some of the collisions lead immediately to radiation. The most intense features in the visible spectrum arising from direct impact excitation are presumably those mentioned earlier in Section 2.2, though the contribution to the allowed first negative and Meinel band systems of N_2^+ will be negligible compared to resonance scattering and to fluorescence scattering (Dalgarno and McElroy [51]).

Resonance scattering will also provide the major contribution to the resonance transitions of N_2 and O which appear in the ultraviolet. However, from an analysis of dayglow observations of the oxygen line at 1304Å, Donahue and Fastie [52] have concluded that, in addition to resonance scattering and to Ly-β fluorescence, there is a weak source located in the F region near 190 km. Donahue and Fastie have tentatively suggested that the excited atoms may be produced by dissociative recombination of O_2^+ or NO^+ in highly excited vibrational levels but impact excitation by photoelectrons may be a more efficient mechanism. Although detailed calculations are required in order to test the hypothesis of impact excitation, there seems little difficulty in obtaining the required flux of 1304Å radiation. Preliminary calculations suggest an intensity profile peaking near an altitude of 250 km for a solar elevation angle of 30° rather than near 200 km as Donahue and Fastie require.

The origin of a weak line at 1355Å, observed by Donahue and Fastie and tentatively identified by them as the oxygen multiplet $(2p)^4\ {}^3P - (2p^3)\ 3s\ {}^5S$, may also be electron impact excitation. Other weak oxygen lines, such as the auroral lines 7774Å and 8446Å, should be present in detectable intensities. An additional source of the line at 8446Å, which has been observed during twilight by Shefov [53], is absorption of solar Ly-β radiation (Swings [54], Shlovskii [55], and Brandt [56]).

Fast photoelectrons may also produce dayglow luminosity indirectly by populating metastable levels, an example of special interest being the helium line at 10830Å observed during twilight by Shefov and by Scheglow and during a solar eclipse by Shaiskaya (cf. Shefov [57]). Krassovsky [58] and Shefov [59] have attributed the line to resonance scattering by metastable 2^3S helium atoms. The main production mechanism is apparently impact excitation by fast photoelectrons (Shefov [57]) and the main loss mechanism is apparently the Penning ionization process (Ferguson [60]). Preliminary calculations suggest that the observed intensity of 1 kilorayleigh can be explained only by postulating helium concentrations greater than those given by Kockarts and Nicolet [61].

Resonance scattering by the metastable $A^3\Sigma_u^+$ state of nitrogen may lead to a considerable intensity of the first positive band system; the measured lifetime of the $A^3\Sigma_u^+$ state has been reported variously as 2.0 ± 0.9 sec (Carleton and Oldenberg [62]), 0.08 ± 0.04 sec (Dunford [63]) and 0.9 sec (Zipf [64]).

6.2 Electron and Ion Temperatures

The relationships between the temperatures of the electrons, the positive ions and the neutral particles which constitute the ionosphere are fundamental to the interpretation of its behavior. The theoretical studies of the effect of solar ultraviolet radiation and the fast photoelectrons it produces ([49], [28], Hanson [65] and Dalgarno [66]) show that departures from temperature equality are to be expected at altitudes above about 150 km, the difference between the electron temperature and the heavy particle temperature attaining at midday a maximum somewhat greater than 1000°K at an altitude of about 220 km and decreasing rapidly as the altitude increases to 300 km. These conclusions are in substantial agreement with the Langmuir probe measurements (cf. Bourdeau [67]).

According to the theoretical studies, the difference between the electron temperature T_e and the positive ion temperature T_i should decrease rather slowly with increasing altitude above the peak of the F region. The difference may persist over several hundred kilometers, the predicted magnitude of $T_e - T_i$ depending sensitively upon the assured density of the ambient electrons ([65], [66]).

It has been suggested ([28]) that near sunrise the heat flux density may exceed the critical value (9) and preliminary calculations by Dalgarno [66] and Bourdeau [68] support the conjecture. Dalgarno [66] has pointed out that the anomalous rise of T_e to a value greater than $3T_i$ should be accompanied by a red glow. A preliminary calculation suggests that the glow is located between 400 and 500 km and may attain an intensity of several hundred rayleighs. There is evidence from satellite observations (cf. [68]) and from equational backscatter observations (Bowles, Ocho and Green [69]) that $T_e - T_i$ is large at sunrise but the reported magnitudes do not exceed $2T_i$.

Measurements of T_e and T_i at altitudes above 300 km are in apparent contradiction. Bourdeau [67] has shown that rocket and satellite observations at mid-latitudes in quiet conditions can be satisfactorily explained by assuming that T_e, T_i and the neutral gas temperature T_n are approximately equal, a conclusion that is in harmony with the observations of backscatter at the equator reported by Bowles, Ocho and Green [69] but not with the observations of backscatter by Evans [70] and Pineo and Hynek [71] at higher latitudes. Evans (private communication, 1963) and Bourdeau [68] have emphasized that there may be a significant variation of T_e with latitude as was indeed suggested by the rocket measurements of Spencer, Brace and Carignan [72].

The electron temperature in the ionosphere is very sensitive to small disturbances [66] and the flux of electrons postulated by Mariani (cf. Section 2.1) may well be sufficient to explain the results of the recent analysis by Evans (private communication, 1963) of backscatter data at a geomagnetic latitude of 54°N, which show that the ratio of T_e to T_i reaches a maximum value of nearly 2.4 at an altitude of 450 km. That T_e should considerably exceed T_i at these altitudes appears to preclude a possible explanation involving electric fields.

If the values of T_e/T_i obtained by Evans are correct, then in addition T_i may exceed T_n by several hundred degrees in the altitude region between 500 and 600 km (Dalgarno [66]).

The backscatter observations and the rocket and satellite measurements are consistent in showing that temperature equality normally prevails at night. The possible flux of soft electrons is accordingly less than 0.03 erg cm^{-2} sec^{-1}.

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ACKNOWLEDGMENTS

This manuscript was begun at the Joint Institute of Laboratory Astrophysics in Boulder, Colorado, and completed at the Goddard Institute for Space Studies in New York. The work was supported by the National Aeronautics and Space Administration under Contract No. NASw-701.

I am indebted to Dr. L. Branscom and Dr. R. Jastrow for their hospitality. I am indebted also to Mr. J. Walker for some valuable discussions.